Large Topographic Rises on Venus: Implications for Mantle Upwelling

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Abstract

Topographic rises on Venus have been identified that are interpreted to be the surface manifestation of mantle upwellings. These features are classified into groups based on their dominant morphology. Atla and Beta Regiones are classified as rift-dominated, Dione, western Eistla, Bell, and Imdr Regiones as volcano-dominated, and Themis, eastern Eistla and central Eistla Regiones as corona-dominated. At several topographic rises, geologic indicators were identified that may provide evidence of uplifted topography (e.g., volcanic flow features trending upslope). We assessed the minimum contribution of volcanic construction to the topography of each rise, which in general represents less than 5% of the volume of the rise, similar to the volumes of edifices at terrestrial hotspot swells. The total melt volume at each rise is approximated to be 10^4- 10^6 km^3. The variations in morphology, topography and gravity signatures at topographic rises are not interpreted to indicate variations in stage of evolution of a mantle upwelling. Instead, the morphologic variations between the three classes of topographic rises are interpreted to indicate the varying influences of lithospheric structure, plume characteristics and regional tectonic environment. Within each class, variations in topography, gravity, and amount of volcanism may be indicative of differing stages of evolution. The similarity between swell and volcanic volumes for terrestrial and venusian hotspots implies comparable time-integrated plume strengths for individual upwellings on the two planets.

INTRODUCTION

Large volcanic edifices on Venus are concentrated primarily in the equatorial region of the planet and arc typically associated with regional topographic rises. Major topographic features interpreted to be hotspots based on their topography, associated volcanism, and apparent depth of compensation, include: Atla Regio [Senske *et* cd., 1992], Beta Regio [McGill *et al.*, 1981; Campbell et *al.*, 1984], Bell Regio [Basilevsky *et al.*, 1986; Janle *et al.*, 1987], Dione Regio [Keddie and Head, 1994a], Eistla Regio (eastern, central and western) [Senske et *al.*, 1991; Senske ***et al.,*** 1992; Grimm and Phillips, 1992; McGill, 1994], Imdr Regio, and Themis Regio [Stofan et *al.*, 1992] (Table 1, Figure 1). The Venus rises have diameters on the order of 1000 km, similar to terrestrial hotspot diameters [Monncreau and Cazenave, 1990]. Rises on Venus exhibit great variations in their morphologic and topographic characteristics [Stofan *et al.*, 1989; Bindschadler *et al.*, 1992; Senske *et al.*, 1992], as well as their gravity signatures [Smrekar and Phillips, 1994]. Many topographic rises exhibit abundant volcanism, generally in the form of large shield volcanoes and lava flood plains [Head *et al.*, 1992]. Other rises, such as western Eistla, also are characterized by smal l (<50 km diameter) and intermediate scale edifices. Over half of the volcanic rises have coronae on or near their flanks [Senske *et al., 1992;* Stofan ***et al.,*** 1992]. Evidence of extensional deformation is present at all Venus volcanic rises, ranging from small graben to belts of fractures and troughs to major rift systems. Differences between individual topographic rises on Venus has previously been attributed to differences in geologic setting [Senske *et al.*, 1992; Keddie and Head, 1994a] or to variations in plume geometry [Keddie and Head, 1994*a*].

The characteristics of volcanic rises can be compared to predictions for hotspot evolution (e.g., Griffiths and Campbell, 1991; Houseman and England, 1986; Hill, 1991; Smrekar and Parmenticr, 1994). In this paper, wc conduct an integrated study of topographic rises on Venus in order to identify gross properties that can be linked to hotspot evolution, building upon earlier, local studies (e.g., Senske *et* al., 1992; Grimm and Phillips, 1992; McGill, 1994). We document the major geologic/morphometric characteristics and gravity signatures of each rise and classify them according to morphologic and topographic characteristics, estimate the relative contributions of uplift vs. volcanic construction, and compare the venusian volcanic rises to terrestrial hotspot swells. Finally, we explore models to account for the morphologic and topographic differences between topographic rises on Venus.

*Geology **of** Venus Rises*

At each rise examined, the relative abundance of major morphologic features varies. Rises are clearly separable on the basis of the relative importance of rifts, major volcanic edifices, and coronae. Rises are therefore classified as rift-dominated, volcano-dominated and corona-dominated. Images and altimetry of most of these features can be found in Bindschadler *et al. [1992]* and Senske et *al.* [1992].

Rift-dominated. Two of the rises, Atla and Beta Regiones, are classified as rift-dominated (Figure 2, Table 1). Each is cut by a major axial rift valley that extends for thousands of kilometers, far beyond the topographic swell. Some other rises are associated with minor rift structures or belts of graben, but these zones of extension extend for hundreds rather than thousands of kilometers and are less intensively deformed. The rifts at Atla and Beta are approximately 50-100 km wide and up to *2 km* deep, and are characterized by broad zones of parallel to subparallel radar-bright linear features interpreted to be normal faults. [Campbell et *al.,* 1984; Stofan *et al.,* 1989; Solomon *et al., 1992;* Senske et *al.,* 1992]. At Atla, the central rift connects with the Hecate, Parga and Dali/Diane Chasmata systems. Devana Chasma in Beta Regio extends to the south toward Phoebe Regio, and is connected to the Hecate system and a broad, diffuse zone of extension and volcanism which links Beta and Eistla Regiones. Ada and Beta contain large shield volcanoes (Maat and Ozza Montes, and Theia Mons, respectively), and have few associated coronae. Coronae at both Atla and Beta Regiones lie off of the rise [Senske *et al.,* 1992], and do not appear to be directly related to rise formation. Geologic studies (e.g., Stofan et ***al.,*** 1989; Senske *et al.,* 1992) indicate similar evolutionary sequences at Atla and Beta, with volcanism and extension overlapping in time.

Volcano-dominated. Imdr, western Eistla, Bell, and Dione Regiones arc broad rises dominated by one or more large-scale (>300 km diameter) volcanic edifices (Figure 3, Table 1). The edifices tend to be 1-2 km high, and are surrounded by extensive radar-bright and dark flows. At each volcano-dominated rise, minor extension is present. Guor Linea at western Eistla Regio is the best-developed extension zone associated with a volcano-dominated rise. Western Eistla Regio has two major shields, several smaller edifices, and two coronae on its northern flank [Senske *et al.*, 1991; Senske et ***al.,*** 1992; Grimm and Phillips, 1992], while Dione Regio has three large shields [Keddie and Head, *1994a].* Imdr Regio has one large unnamed shield. Bell Regio has two major edifices and a corona [Basilevsky *et* al., 1986; Campbell and Rogers, 1994]. Imdr and Dione Regiones have no associated coronae.

An evolutionary sequence can be determined at several of the volcano-dominated rises. Cross-cutting and embayment relationships indicate that faulting has both pre- and postdated volcanism at western Eistla Regio, while the two major edifices formed synchronously [Senske *et al., 1992].* Wrinkle ridges surrounding western Eistla are interpreted to have formed after the topographic rise, but prior to the formation of the volcanic edifices of Sif and Gula Montes [Basilevsky, 1994]. At Imdr, most of the swell displays sinuous ridges interpreted to be wrinkle ridges (i. e., Squyres *et al.,* 1992; McGill *et al., 1993)* (Figure 3). Similar ridges are found in the plains surrounding Imdr Regio, suggesting that wrinkle ridge formation preceded uplift at Imdr, and that the volcanism has been confined largely to the major edifice.

Corona-dominated. Themis, central Eistla, and eastern Eistla Regiones are characterized by clusters of coronae (Figure 4, Table 1). A related feature is Mnemosyne Regio, a corona cluster which lacks a distinct swell [Stofan and Head, 1989]. The coronae in each cluster are typically 200 to over 500 km across, and vary in spacing. At each rise, the coronae exhibit abundant volcanism, including extensive radiating flows and small to intermediate scale edifices. Magee Roberts and Head [1993] have noted that coronae located along extension zones have increased amounts of volcanism, and they have proposed that the intersection of upwellings with extensional zones is a controlling factor in the amount of melt produced at a corona. Central Eistla Regio is dominated by three coronae, and also contains several large volcanic constructs and calderas [Stofan *et al.,* 1992; McGill, 1994]. Sappho is classified as a corona, as it possesses a distinct annulus of tectonic features; however, it has many similarities to a volcanic edifice.

Themis Regio has five major coronae (Figure 4), and is unique in that it lies at the terminus of the Parga Chasma corona chain [Stofan *et aL, 1992]. There* are four coronae in eastern Eistla Regio, the largest of which is Pavlova Corona. Themis Regio is the only one of the three corona-dominated rises that contains any significant extensional deformation. A graben lies along the axis of the highest topography within the largest corona. Minor extensional features also cuts across the swell, continuing from Parga Chasm a. Fractures and graben are much less common than along the rest of Parga Chasma, and are embayed by corona-related flows in places, indicating that corona formation generally postdated extension. At central Eistla Regio, McGill [1994] found that coronae formed prior to volcanic edifices, but coeval with deformation.

Topography of Venus Rises

In order to estimate the size and volume of the volcanic rises, measurements were made of the maximum height and diameter using Magellan altimetry data [Ford and Pettengill, 1992] (Table 1). The maximum height was determined by examining a series of profiles across the topographic rise in regions not visibly dominated by volcanic constructs. The topographically highest swells are the rift-dominated rises, with Beta Regio lying 2.1 km above the surrounding plains and Atla Regio at 2.5 km above the surrounding plains (Table 1). The volcano-dominated and corona-dominated swells all lie 1.0- 1.8 km above the surrounding plains, closer to the typical height of terrestrial swells (Table 2). The broad swell of Dione Regio is at best only marginally detectable, and is less than 500 meters in height.

Swell diameters were determined by identifying the break point in slope around the base of the swell. This was done using both topographic profiles and using altimetry data displayed in image form. An interactive display program was used to density-slice the altimetry data in image form to determine the break in slope. Minimum and maximum rise diameters were estimated, due to the uncertainty in determining an accurate break in slope at each swell (Table 1). Minimum swell diameters range from 1000 to 2000 km, and maximum diameters from 1400-2500 km. Beta and western Eistla Regiones are the largest volcanic rises; Imdr, Bell, Dione and central Eistla Regiones are the smallest.

Swell and Edifice Volumes

The volume of material in each of eight volcanic rises was calculated. The break in slope at the rise edge and the average of all elevations within the rise were used to obtain the mean height of the rise. This was multiplied by the area within the rise as defined by that same break in slope. The baseline elevation was found using the same interactive image display program used to find the break in slope of the rise. Two estimates of baseline elevation were made in order to establish upper and lower bounds on the volume of each rise. The volumes thus calculated (Table 1) arc related to the amount of volcanic construction and/or uplift for each rise.

Beta Regio has the largest volume of any of the volcanic rises (Table 1). Some of this volume is probably unrelated to rise-forming processes such as magmatism and uplift, and may be instead due to the presence of thickened crust that predates volcanism and rifting at Beta Regio [Senske et ***al.,*** 1992]. The rest of the rises exhibit a relatively continuous gradation in volume, with Atla and western Eistla Regiones as the largest and Imdr and central Eistla Regiones as the smallest. We could not obtain a reliable estimate for Dione Regio, in part due to the fact that Magellan topographic coverage of the region is incomplete, but also due to difficulties in clearly distinguishing the topographic rise from the surrounding plains.

A lower bound on the volume of volcanics was estimated, where possible, by finding the volumes of major volcanic features on each rise. This was done by determining a baseline elevation for the volcanic construct in the same manner described above for the rise as a whole. Utilizing the height and diameter of the construct and assuming a conical shape, an approximate volume for the volcanics was then calculated. This obviously represents a minimum contribution by volcanism, as undoubtedly part of the rise is composed of flows and intrusive. However, at each rise examined, no flows could be distinguished on rise surfaces other than those related to major shields, small constructs, or coronae. An exception to this are minor flows at western Eistla Regio and Atla Regio that appear to emanate from rift fractures [Senske et *al.*, 1992]. The maximum volume of volcanics (>400,000 km^3) was found at Atla Regio. In general, the volume of volcanic edifices was estimated to be at least 5% of the volume of the rise.

Gravity Signatures of Venus Rises

The relationship between gravity and topography provides an indication of the mechanism by which surface features are supported. Previously, both regional and global studies were carried out using Pioneer Venus data [e.g. Kiefer and Hager, 1991; Smrekar and Phillips, 199 1; Grimm and Phillips, 1992]. The apparent depths of compensation (the depth of compensation assuming isostatic support) in excess of 100 km determined for volcanic rises suggest that hotspots are most likely supported by mantle plumes.

Using Magellan gravity data and the orbit simulation software, ORBSIM [Phillips *et aL,* 1978], ADCs for Imdr, Dione, Themis, and central Eistla Regiones were estimated, following the approach of Smrekar and Phillips [1991]. Magellan gravity data were obtained by measuring the change in spacecraft velocity along the path between the spacecraft and Earth and are thus referred to as line-of-sight data. The data are analyzed by calculating, in the line-of-sight geometry, the gravitational attraction of topography and a corresponding grid of compensating masses at depth. A single depth of compensation is obtained by finding a best fit to the structure and amplitude of the anomaly. ADCS for Beta, Atla, western Eistla, and Bell Regiones in Table 1 are from Smrekar [1 994]; the ADC for eastern Eistla Regio was obtained separately [Bindschadler, 1993]. These latter values are a more robust indicator of plume depth because they are based on all available Magellan gravity data for each region, which was filtered to retain only wavelengths comparable to the topographic swell. Such estimates tend to yield somewhat lower values than those obtained from the single-orbit method described above. A general correlation of the compensation depth with height of volcanic rise and class of feature is visible (Figure 5). The rift-dominated rises, Beta and Atla Regiones, have the greatest topographic relief (> 2.0 km), and are compensated at depths of 225 and 175 km, respective y. Volcano-dominated rises exhibit intermediate elevations, 1.5 to 2.0 km, and are compensated at depths of 125 to 260 km. Corona-dominated rises have ADC's of- 100 km and swell heights of 1.0 to 1.5 km.

Detailed analysis of Magellan gravity at four hotspots, Beta, Atla, Bell, and Western Eistla Regiones [Smrekar, 1994] provides further insight on compensation mechanisms. Analysis of the admittance spectra in three of these regions supports an active mantle plume interpretation. At Atla Regio, the long wavelength depth of compensation is 175±35 km, the effective elastic thickness is approximately 30 km, and there is evidence that the elastic plate is being loaded from above by volcanoes at short wavelength and from below at long wavelengths suggesting a buoyant mantle plume. The gravity signature of Bell Regio is very different. The long wavelength depth of compensation is 125±35 km, the effective elastic thickness is 50 km at long wavelength, and 30 km at short wavelengths. Modeling of the coherence at Bell Regio gives a ratio of bottom-to-top loading of 0.1. The relative] y shallow compensation depth, relatively thick elastic thickness, and the small fraction of bottom loading all indicate that the plume is in a late stage of evolution, possibly even extinct. The data quality at Beta and Western Eistla Regio was low due to poor line-of-sight geometry, spacecraft altitude, and possible ringing in the data reduction [e.g., Smrekar, 1994], and thus did not permit estimates of the effective elastic thickness and or the location of loads. However, the large apparent depths of compensation, 200±35 km at Western Eistla Regio and 225±35 km at Beta Regio, suggest the presence of active mantle plumes.

DISCUSSION

Contributors to Rise Topography on Venus

Two processes are likely to contribute to the production of broad topographic swells on Venus. One is the plume or thermal anomaly, which can produce heating and thinning of the thermal lithosphere, and dynamic uplift due to viscous forces caused by the rising plume. The second source is isostatic uplift due to magmatic thickening of the crust and localization of chemically buoyant melt residuum from pressure-release melting. Since the amount of magmatism and the amount of uplift due to the plume itself are most directly linked to the *strength* and depth of the upwelling, it is critical to attempt to distinguish uplift from volcanic construction and to place some bounds on the contribution from each process.

An obvious lower bound on the volume of volcanics is the volume of the volcanic edifices (Table 1). To more accurately constrain the lower bound requires estimation of the volumes of hotspot-related flows that extend far from individual constructs. However, most rise surfaces far from edifices are dominated by radar-dark to radar-mottled plains surfaces which are not easily distinguished from off-rise plains, making it very difficult to distinguish possible rise-related flows from pre-existing plains. In the *other* extreme, the entire volume of the swell and its isostatic root plus edifices can be considered an upper bound on the volume of volcanics. The reality is likely to lie between the extremes of the topographic swell being entirely a volcanic constructor entirely to due to uplift.

Another important factor in assessing the crustal volume of rises is the ratio of extrusive volcanic volume to the total melt volume. Seismic and gravity data at terrestrial rise.s indicate that the ratio of the volume of the volcanic edifices to the total melt volume is 1:2 to 1:10 [White, 1993; Watts *et al.*, 1985; ten Brink and Brother, 1987; Wolfe *et al.*, 1994]. With the average rise having extrusive volumes on the order of 5% of rise volume, or 10^4-10^5 km^3, the total melt volume may be 10^4-10^6 km^3. However, if the intrusive volcanism is crustall y compensated, the topography will increase less than 100 m, assuming a volcanic volume of 10^7m^3 (an order of magnitude larger than edifices at Atla) and a radius of 150 km [Smrekar and Parrnentier, 1994]. Obviously, the amount of constructional volcanism may differ significantly from rise to rise on Venus. For example, Dione Regio appears to be dominated by volcanic construction, while Imdr Regio has very localized volcanism and a significant portion of its topography contributed by uplift. In addition, Sapas Mons, which is not located on a topographic swell, has been suggested to be the result of a small plume resulting in no uplift and relatively limited volcanism [Keddie and Head, 1994 b].

An upper bound on the amount of uplift is given by the height of the topographic swell minus the volcanic edifices, while paleoslope indicators provide a lower bound on the amount of uplift at some rises. We have identified two possible paleoslope indicators, one in Beta Regio and one in western Eistla Regio. In both locations, volcanic features appear to disregard the local topographic gradient. In western Eistla Regio, a small volcanic center lies to the northeast of Sif Mons at 29.5°N, 356°. Radar bright materials interpreted as flows extend to a uniform distance from the edifice, despite the location of the volcanic center on the flanks of topographic swell (Figure 6). The bright materials south of the edifice extend upslope for several tens of kilometers, with distal portions lying at least 200 rn higher than the proximal portions of the flow.. This implies that the edifice was emplaced prior to at least some of the uplift associated with the formation of the western Eistla r ise. An additional paleoslope indicator in western Eistla is a dark-floored impact crater which lies on the flanks of the rise (Kunitz, at 14.5°N, 350.9°E). Connors [1992] found that the tilt of the crater floor is the same as the slope of the topographic swell. The dark floor material is interpreted to be an initially level deposit of impact melt.

Another possible indicator of uplift is a lava channel located on the western flank of Beta Regio (Figure 7). The energetics of lava channels such as lunar rilles dictate that channels narrow downstream, unlike channels carved by water [Baker *et aL,* 1992]. It is primarily on this basis that the channel on the flank of Beta Regio is interpreted to be flowing to the southeast in an uphill direction. The shape of the erosional islands in the channel tend to support this conclusion (T. Parker, pers. comm.). This indicates that volcanism associated with emplacement of the lava channel must have predated uplift. In all of these cases, a minimum of 200 m of uplift is indicated which represents about 10% of the total rise relief.

While it is not possible to completely distinguish constructional rise topography (due to magmatism) from that due to the underlying plume, plumes or other deep-seated anomalies within the mantle arc the predominant source of long-wavelength rise topography. If rises are primarily constructional, then extremely large volumes of magma must be emplaced without creating surfaces that are distinguishable from the bulk of venusian plains regions. Hotspots that are also sites of regional extension, such as Themis, Atla, and Beta Regiones, may have increased amounts of melt production [Magee Roberts and Head, 1993]. Moreover, a very large fraction of crustal compensation should give a shallower compensation depth than is found at large swells. Morphological indicators demonstrate that a minimum of 200 meters of uplift has occurred on the flanks of western Eistla and Beta Regiones.

*Implications **of** Rise Characteristics*

Several theoretical and laboratory experiments have simulated the interaction of mantle upwellings with the lithosphere [Olsen and Nam, 1986; Griffiths *et al.*, 1989; Griffiths and Campbell, 1991; Smrekar and Parmentier, 1994]. These studies predict that a rising diapir will flatten out as it encounters the lithosphere, first producing a topographic dome, which may evolve to a more plateau-like rise as the plume head flattens out. Since initial uplift of the topography precedes the penetration of the plume into the Ii thosphere, melting will lag behind the uplift [Griffiths and Campbell, 1991; Smrekar and Parmentier, 1994]. The general sequence of evolution of geoid and topography is expected to be the same regardless of reasonable variations in lithospheric or plume properties. "l'he geoid-to-topography ratio over a rising plume is predicted to be very large when the. negative mass anomaly of the plume is still deep in the mantle and to decrease as the plume nears the surface and flattens out [Smrekar and Parmentier, 1994]. Early stage hotspots are predicted to have large geoid-to-topography ratios, moderate to large topographic uplift, possible extension, and little volcanism. Intermediate stage hotspots should have intermediate geoid-to-topography ratios, moderate to large topographic uplift, possible extension, and significant volcanism. Late stage hotspots will have slightly lower geoid-to-topography ratios, and lower topography.

Based on this generalized sequence of evolution, all topographic rises included in this study appear to be in the intermediate to late stages of evolution. We do not see any topographic rises with little volcanism and very large GTRs indicating the earliest stage of evolution. The low topography and low GTRs of Themis, Dione, Bell and Eastern Eistla Regiones may be indicative of more advanced hotspot evolution. We generally found uplift and higher volumes of volcanism to be strongly related. The exceptions to this are Imdr Regio, where there is a 1.6 km topographic rise and relatively little volcanism, and Dione Regio, where significant volcanism exists with relatively low topography indicating little uplift.

In addition to gravity, topography and the amount of volcanism, the timing of extension may provide insight into the evolutionary stage of a volcanic rise. Simple models of upwelling predict that uplift precedes volcanism [Campbell and Griffiths, 1990], however, the timing of volcanism versus extension is more difficult to predict. If the lithosphere is relatively cold and strong before the plume arrives, extension may not occur until the lithosphere is thermally weakened [Houseman and England, 1986; Hill, 1991]. on Earth, there is both evidence of rifting preceding volcanism and volcanism preceding rifting [Hooper, 1990; Hill, 1991]. Despite the high surface temperature on Venus, some gravity and topography models [Sandwell and Schubert, 1992; Johnson and Sandwell, 1994; Phillips, 1994; Smrekar, 1994] and rock mechanical studies [Mackwell et *al.*, 1994] suggest that the lithosphere is comparable in strength to Earth's. At the venusian topographic rises, there is no evidence that significant deformation has postdated major volcanism (e.g., rifted apart volcanoes), but there is evidence that volcanism postdates major rifting (e.g., Theia at Devana, Gula at Guor), and that uplift has postdated some volcanism (e.g., western Eistla Regio, Beta Regio). At other sites on Venus, such as corona chains, evidence exists that volcanism and extension have occurred concurrently [Baer *et al.*, 1994; Hamilton and Stofan, 1993]. Based on the evidence at Venus rises, volcanism postdates major extension, which is not consistent with simple models of upwelling beneath a thick, cold lithosphere. However, the difficulty in identifying early-stage volcanic flows necessitates further, more detailed mapping studies.

If all of the hotspots are in a relatively similar evolutionary state, what factors can account for the variations seen at venusian topographic rises? Although the general sequence of plume evolution is always the same, morphologic, topographic and gravity signature differences between volcanic rises can be caused by the following factors: 1) differences in plume strength (duration and magnitude); 2) differences in lithospheric chemical and thermal structure; and 3) differences in regional geologic setting. For example, thinning of a preexisting layer of buoyant residuum can reduce topography while increasing the GTR [Smrekar and Parmentier, 1994]. Large volumes of pressure-release melting will isostatically increase the topography and GTR by introducing both buoyant residuum at depth and thickening the crust. Regional extension that thins the lithosphere is one way to enhance pressure-release melting. Greater plume buoyancy flux will also increase topography and GTR. Thus difference in evolutionary stage is not the only factor that can account for large differences in topographic relief and GTR between hotspots.

Beta and Atla Regiones have the largest swell heights, volumes, and apparent depths of compensation. Extension at both sites may have facilitated increased pressure-release melting and contributed to swell heights and large ADCs. The greater scale of rifting at rift-dominated rises relative to other rises is not interpreted to indicate a hotter, weaker lithosphere and a later evolutionary stage; nor are rift-dominated rises likely to evolve into other types of rises. Volumes of volcanics at rift-dominated rises exceed those at the volcano--dominated rises. Thus it is unlikely that major rifts have simply been flooded by volcanism at volcano-dominated rises. However, the large swell heights and ADCS do suggest an intermediate (or earlier than at many other hotspots) stage of evolution at Atla and Beta Regiones. The location of Beta and Atla at tectonic junctions along large-scale chasmata systems suggests that their rift-dominated morphology is primaril y controlled by the regional extensional stress state which has also produced the chasmata systems.

At the corona-dominated rises of central Eistla, Themis and eastern Eistla Regiones, a range of ADCS are seen (Table 1, Figure 5). Modeling of corona formation indicates that small-scale upwellings must penetrate to fairly shallow depths to cause the observed topography [Stofan *et al.*, 1991; Janes et *al.*, 1992]. Shallow, small-scale instabilities related to individual corona may tend to decrease the GTRs at corona-dominated rises. The presence or absence of coronae cannot be used to indicate a particular evolutionary stage at volcanic rises, as coronae are not thought to be linked in an evolutionary sense to volcanoes [Stofan *et cd.*, 1992]. Coronae are also not likely to be hidden by subsequent volcanism, since corona-dominated rises exhibit very large volumes of volcanism. Instead, the presence of coronae at volcanic rises may reflect small-scale convection in the lithosphere induced by the rising plume or instabilities and break up of the plume head [e.g., Griffiths and Campbell, 1991], creating small-scale diapiric upwellings that form coronae.

The volcano-dominated rises also do not appear to represent a 'stage' in hotspot evolution. As discussed above, they do not represent an advanced stage beyond the rift-dominated class. Based on current models of corona evolution *[i.e.,* Stofan *et al.*, 1991; Janes et *al.*, 1992], there is no evidence that volcanoes evolve into coronae. Therefore, volcano-dominated rises are not interpreted to evolve into corona-dominated rises. Within the volcano-dominated elms, it is possible to determine relative stage of evolution based on gravity data. Bell Regio has been interpreted to be more evolved than western Eistla Regio based on analysis of the gravity/topography spectral admittance, as described above [Smrekar, 1994]. Further analysis of gravity, topography, and image data of volcano-dominated rises may result in an evolutionary sequence within this class, but morphology alone does not appear to be a reliable indicator. Volcano-dominated rises are geologically the simplest category of rises and may provide the best insight into the nature of venusian mantle plumes, as they have not been affected by regional extension or small-scale instabilities,

The three morphologic classes of hotspots are interpret.ed to be a result of variations in plume or lithospheric properties rather than different stages of evolution. However, gravity and topography and the presence of volcanism can be used to infer evolutionary stage in some cases. As discussed above, the gravity and topography signatures of Atla, Beta and western Eistla have been interpreted as indicating active mantle plumes, and Bell Regio was interpreted as a late-stage hotspot [Smrekar, 1994]. Without this type of detailed analysis, it is difficult to determine the exact evolutionary stage at most of the volcano- and corona-dominated rises. Their topographic swell heights and ADCS are fairly small and are consistent with intermediate or late stages of evolution [Smrekar, 1994]. One rise that may provide evidence for a relatively early stage of plume development is Imdr Regio, where uplift and limited volcanism could indicate that the plume underlying Imdr has yet to produce significant pressure-release melting. Both of the rift-dominated rises occur in a particular geologic setting, along chasmata systems, where we interpret the regional extensional stress state to control the rift-dominated morphology. Corona-dominated rises are interpreted to reflect break-up of a plume or secondary convection. Volcano-dominated rises appear to he the 'simplest' manifestation of a mantle plume. Therefore, it is apparent that morphology alone cannot be used as a simple indicator of hotspot evolution.

Comparisons of Venusian and Terrestrial Hotspots

Studies have been performed to quantify the height and regional extent of terrestrial oceanic swells [Monnereau and Cazenave, 1990; Davies, 1988]. Estimates of the amount of material extruded onto the surface to form volcanoes shows a large degree of variation for the Earth, ranging from 3 x 10^3 km^3 (those on relatively young oceanic crust) to over 1 x 10^6 km^3 (all volcanoes from along the Hawaiian-Emperor chain; those on old oceanic crust). The amount of volcanic material at Venus hotspots falls within the range of terrestrial values (Tables 1 and 2), suggesting similar amounts of melt generation. The distribution of swell volumes as a function of height (Figure 8 and Tables 1 and 2) shows that those on Venus cluster primarily with their terrestrial counterparts that are located on lithosphere with an age of 90 Ma or greater. Volumes of venusian hotspots are not significantly larger than those on the Earth, however, the ratio of gravity-to-topography for venusian hotspots is a factor of 2-4 higher than for terrestrial hotspots [Smrekar and Phillips, 1991]. On the basis of the lateral extent and height information and the overlap with terrestrial hotspots, it is suggested that the Venus lithosphere may be behaving similarly to old oceanic lithosphere (i.e., little or no low-velocity zone). The absence of a low viscosity zone on Venus has also been inferred from the relationship between gravity and topography [Phillips, 1990; Smrekar and Phillips, 1991; Kiefer and Hager, 1991]. Although Venus has been proposed to have a thick, motionless lithosphere [Turcotte, 1993], hotspot swells have failed to grow as large as the Tharsis Rise on Mars, and no venusian volcanoes have attained a volume comparable to that of 01 ympus Mons. Despite plate motion on Earth, terrestrial and venusian hotspots swells are comparable in si ze. Although the timing of hotspot formation on Venus is fairly unconstrained, this similar size range of terrestrial and venusian hotspot swells implies that the time-integrated plume strengths arc comparable.

CONCLUSIONS

Volcanic rises on Venus exhibit a wide range in morphology, geology and gravity signature. On the basis of morphology, they can be divided into three classes: rift-dominated, volcano-dominated and corona-dominated. These morphologic classes arc interpreted to indicate regional variations in lithospheric structure, tectonic environment, and/or variations in plume strength or duration, rather than an evolutionary sequence, All of the venusian rises arc interpreted to be in intermediate to late evolutionary stages. Detailed examination of gravity and topography can be used to establish an evolutionary sequence amongst the volcano-dominated rises [Smrekar, 1994]. Edifice volumes indicate that the minimum contribution of volcanism at each rise is 10^4-10^5 km^3, with total melt volumes of 10^4-10^6 km^3. Evidence for uplift is present at several volcanic rises, including western Eistla Regio, Beta Regio, and Imdr Regio.

Although there is no evidence for plate motion on Venus, the venusian volcanic rises are similar to terrestrial hotspots in scale and amount of volcanics, implying si hilarities in the time-integrated plume strength on both planets. Deep compensation depths at some venusian rises indicate that mantle upwelling may still be a vigorous process on Venus despite the evidence from the impact crater distribution for little geologic activity today [Schaber *et al.*, 1992; Phillips *et al.*, 1992; Strom *et al.*, 1994]. It is anticipated that more detailed studies of the morphology, topography and gravity signatures within and between each class of volcanic rises on Venus will allow us to distinguish the relative importance of evolutionary stage, lithospheric structure differences, and plume characteristics.

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Table 1, Characteristics of Volcanic Rises on Venus

	Volume of volcanics x 10^3 (km^3)	volume x 10^6 km^3 Minimum	volume x 10^6 km^3 Maximum	Diameter (km) Minimum	Diameter (km) Maximum	ADC (km)	Height of Swell (km)
I. RIFT DOMINATED							
Beta Regio		*3.29*	*6.93*	1900	2500	225	*2.1*
Theia Mons	160.0						
Atla Regio		1.33	*2.62*	1200	1600	175	2.5
Maat Mons	214,0						
Ozza Mons	300.0						
II. VOLCANO DOMINATED							
Imdr Regio		0.61	*0.88*	1200	1400	260	1.6
Unnamed volcano	48.0						
W. Eistla Regio		1.72	*2.85*	2000	2.400	200	1.8
Sif Mons	16.4						
Gula Mons	22.7						
Dione Regio						130	0.5
Ushas Mons	23.4						
Innini Mons	<20						
Hathor Mons	162.3						
Bell *Regio*		0.77	1.22	1100	1400	125	1.2
Tepev Mons	32.6						
III. CORONA **DOMINATED**							
Themis Regio	?	0.94	*1,85*	1650	2300	100	1,5
Central Eistla Regio	?	0.33	0.71	1000	1400	120†	1.0
E. Eistla Regio	?	1,08	1,57	1600	1800	65	1.0

†Grimm and Phillips, JGR, 97, 16035-16054, 1992

Table 2. Characteristics of Terrestrial Hot Spot Swells

	Volume of volcanics x 10^3 (km^3)	Height of Swell (km)†	swell Extent. (km)† x 10^3	Volume of S well (km^3)
Ascenscion	3.4	0.45	1.50±0.2	3.9761e+05
Amsterdam	48.3	0.50	1.20±0.2	2.8274e+05
Azores	48.9	1.20	1.10±0.1	5.7020e+05
Bermuda	21.4	1.20	1.80±0.1	1.5268e+06
Bouvet	34.6	0.70	0.90*0.1	2.2266e+05
canary	148.8	1.50	1.50±0.15	1.3254e+06
Cape Verde	102.8	2.10	1.75±0.15	2.5256e+06
Crozet	83.3	1.70	1.60±0.1	1.7090e+06
Easter	2.0	0.35	1.00±0.2	1.3744e+05
Fernando de Noronha	12.7	1.05	1.00±0.1	4.1233e+05
Galalpogos	8.0	0.60	1.20±0.2	3.3929e+05
Great Meteor	--	1,10	1.10±0.1	5.2268e+05
Hawaii	110.0	1.20	1.45±0.15	9.9078e+05
Hawaii	110.4*			
Hawaiian-Emperor	1079.5*			
Maderia	4.9	1.55	1.00±0.2	6.0869e+05
Marquesas	35.9	0.95	1.30±0.1	6.3048e+05
PitCairn	3,0	0.40	1.30±0.1	2.6546e+05
Reunion	25.9	1.10	1.00±0.1	4.3197e+05
Rio Grande	346.9	0.95	1.40±0.2	7.3121e+05
St. Helena	17.3	0.75	1.10±0.1	3.5637e+05
Samoa	155.2	1.00	0.90±0.1	3.1809e+05
Society	47.9	0.75	0.90±0.1	2.3856e+05
Tubuaii	30.3	0.65	1.00*0.1	2.5525e+05
Tristan-Gough	2.9	0.60	1.00±0.1	2.3562e+05

*Bargar and Jackson, 1974
†Monnerau and Cazenave, 1990

FIGURE CAPTIONS

Figure 1. Topographic map of Venus produced from Magellan altimetry data. Boxes show the locations of volcanic rises.

Figure 2. Magellan radar image of Atla Regio, a rift-dominated rise. The volcanoes of Maat and Ozza Montes (to the southwest and northeast, respectively) are superposed on the bright lineaments interpreted to be rift-related faults. The image is approximately 1800 km across.

Figure 3. Magellan radar image of Imdr Regio. Imdr Regio is classified as a volcano-dominated rise. The image is approximately 2000 km across.

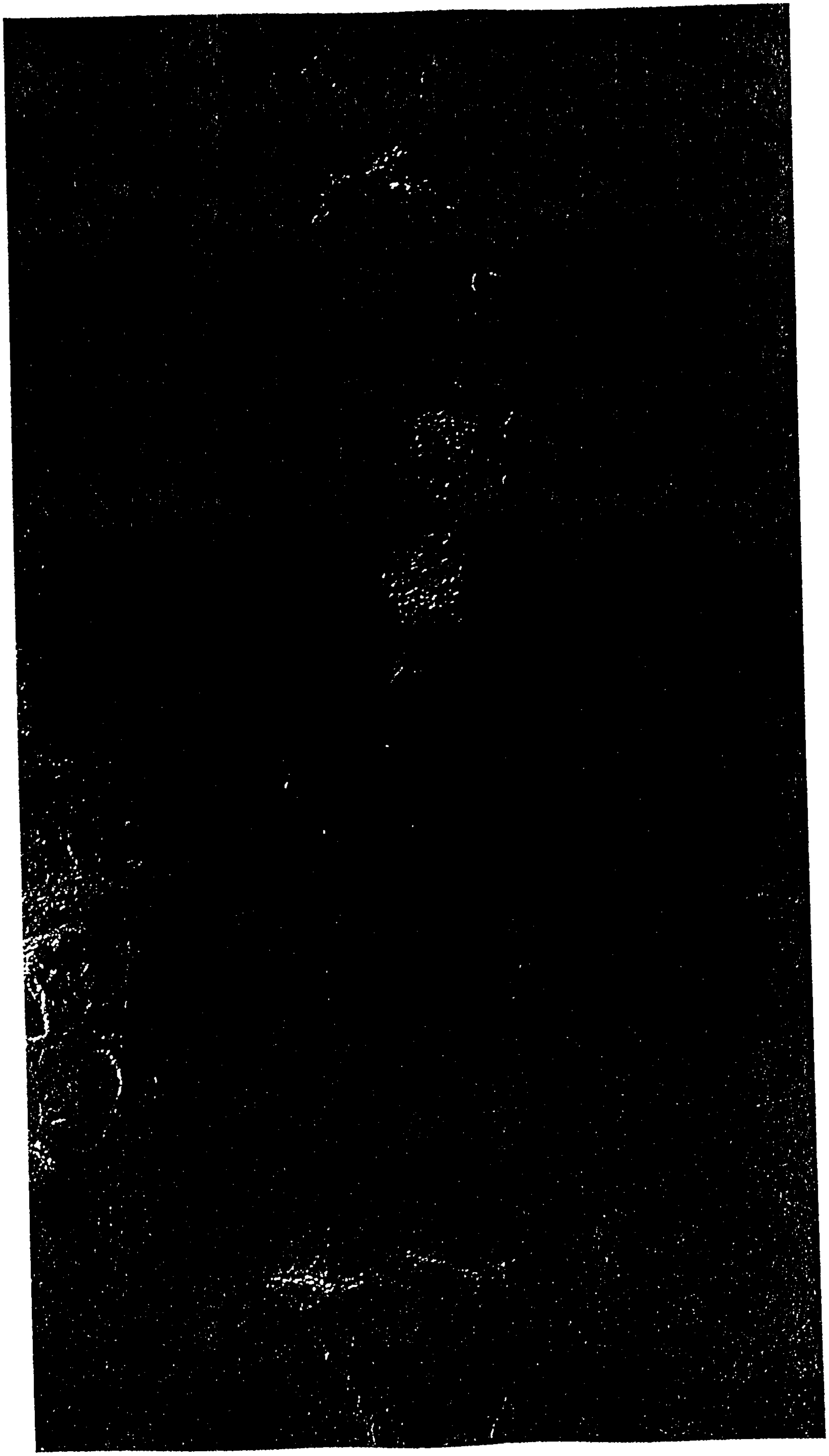
Figure 4. Magellan radar image of Themis Regio, a corona- dominated rise. Themis is located at the termination of Parga Chasma, a chain of coronae which extends to the southeast from Atla Regio. This image is approximately 2700 km across.

Figure 5. Graph showing the relationship between the apparent depth of compensation (ADC) as a function of the height of the volcanic rise.

Figure 6. Magellan radar image of a volcanic edifice in northern western Eistla Regio. Radar bright materials interpreted to be flows from this edifice appear to trend upslope over 200 m on the southern flank. The image is approximately 600 km across; the contour interval is 100 m.

Figure 7. Magellan radar image of a channel located on the western flank of Beta Regio. The channel narrows in the upslope direction, indicating that uplift has occurred after the channel formed. This image is about 220 krn across. The contour interval is 100 m; topography increases to the northwest.

Figure 8. The distribution of swell volumes as a function of height. Terrestrial hotspots on crust less than 90 Ma arc indicated by the crosses while those on crust greater than 90 Ma are indicated by the solid triangles. The Venus swells, represented by the squares, overlap with hotspots on old oceanic crust.



Fig

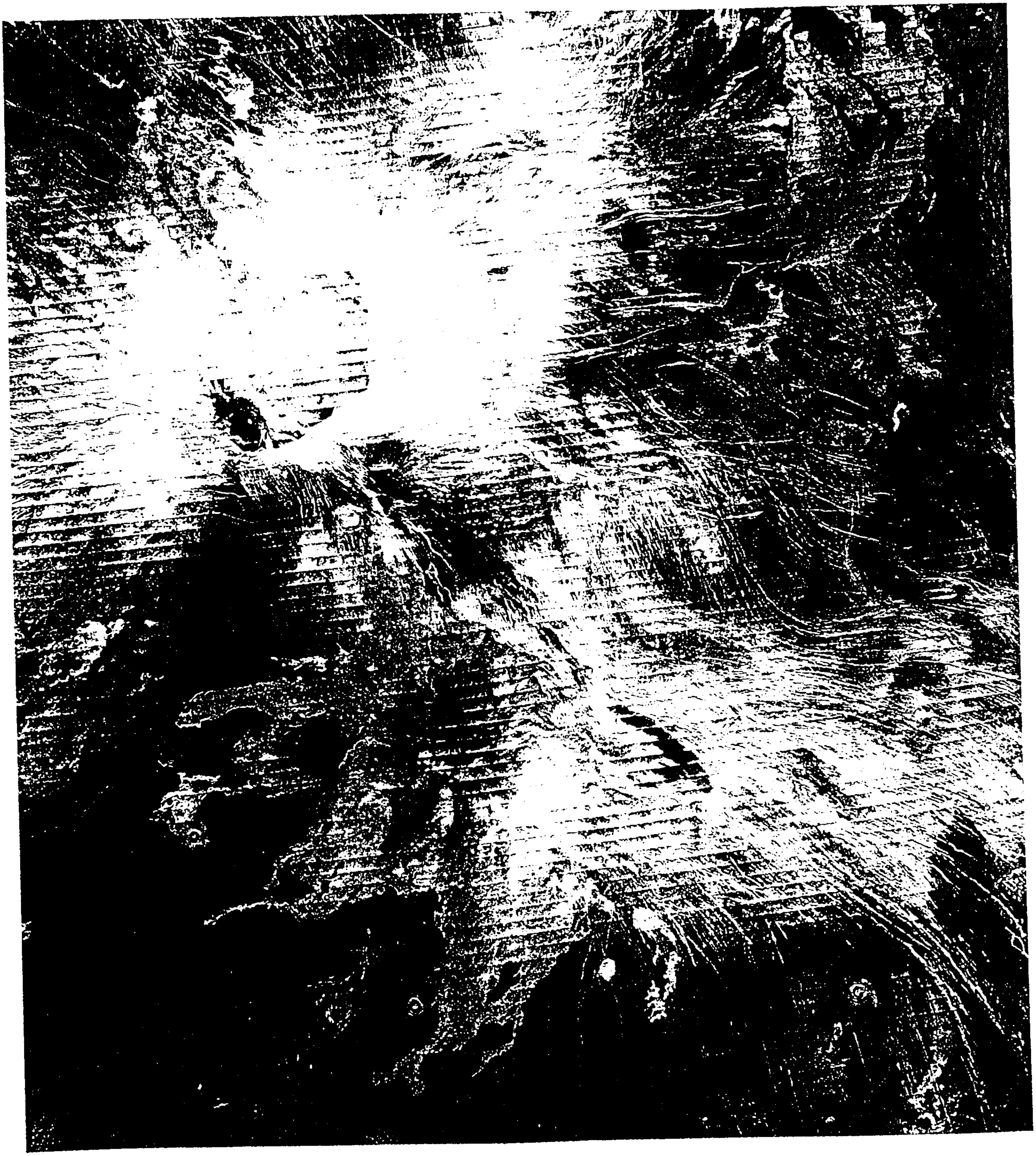


Fig 2

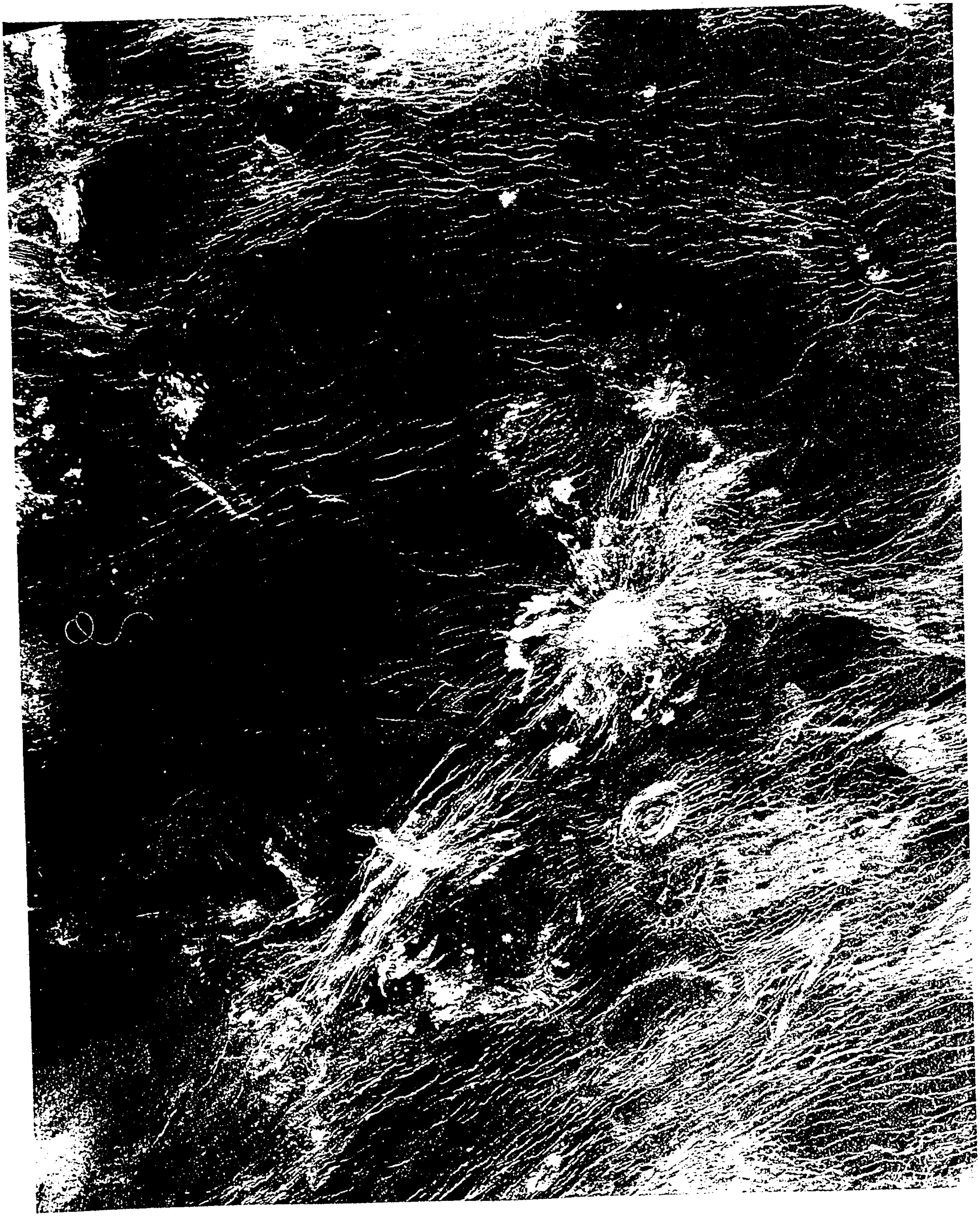


Fig 2

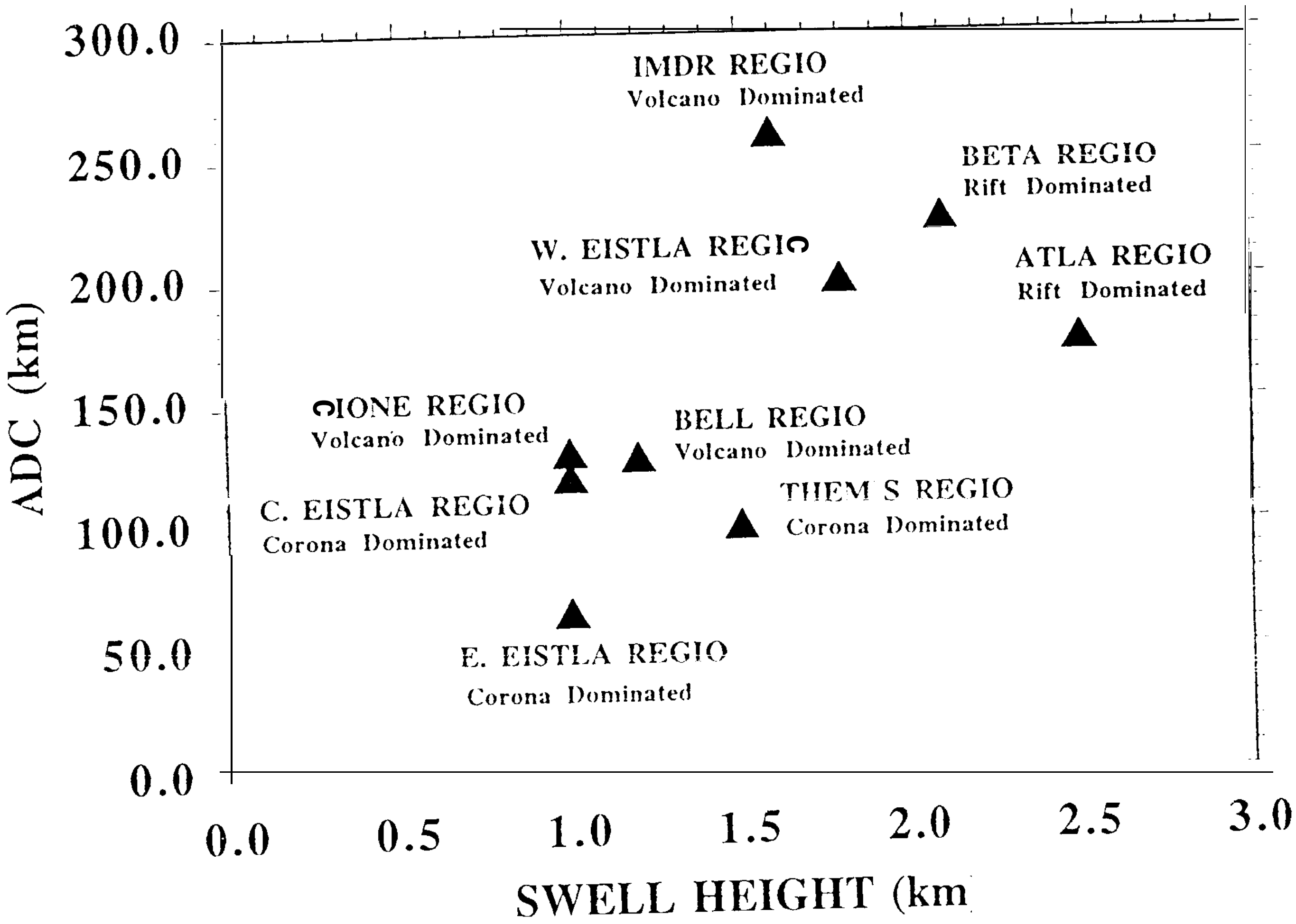
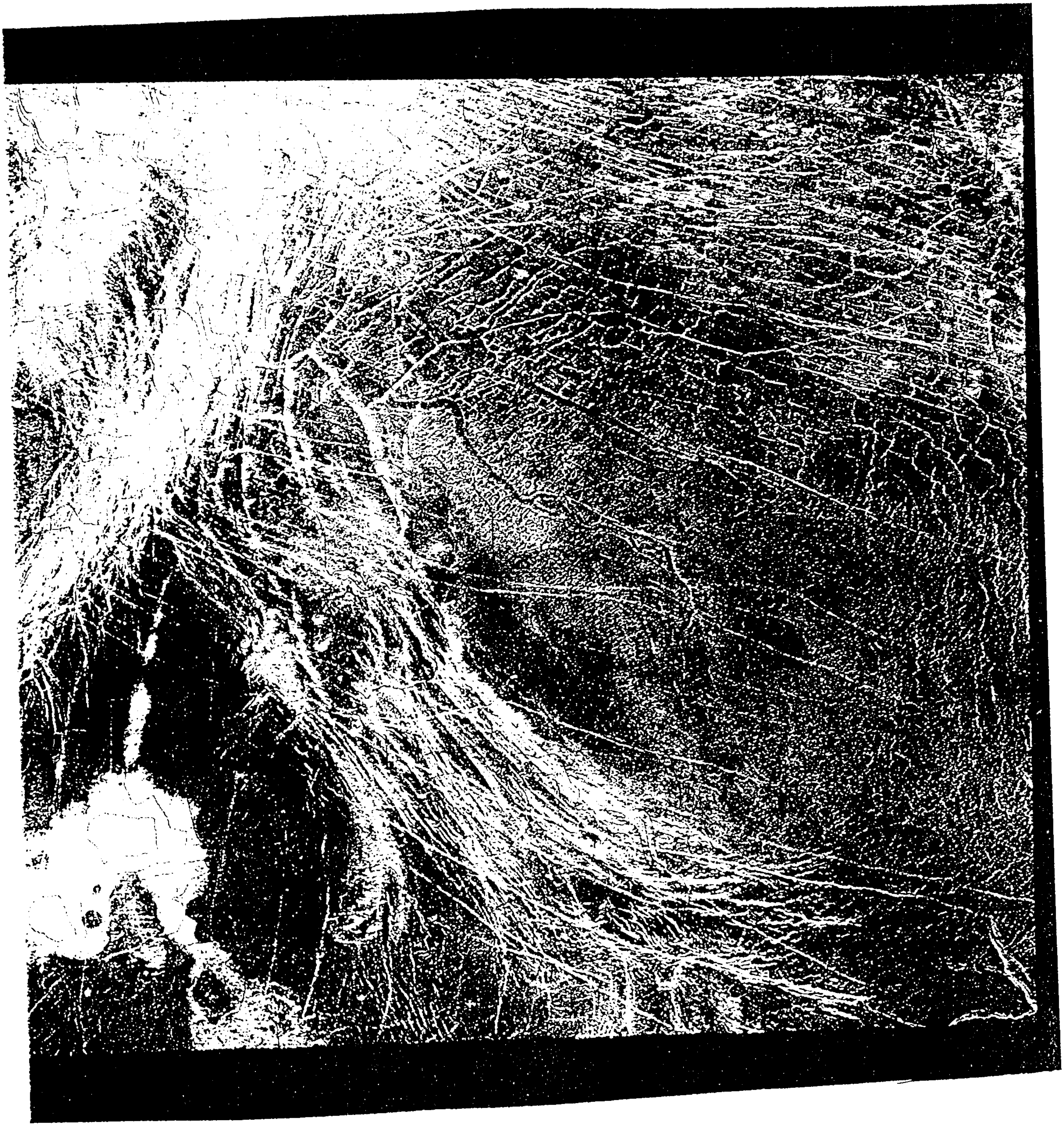

IMDR REGIO
Volcano Dominated
BETA REGIO
Rift Dominated
W. EISTLA REGIO
Volcano Dominated
ATLA REGIO
Rift Dominated
DIONE REGIO
Volcano Dominated
BELL REGIO
Volcano Dominated
C. EISTLA REGIO
Corona Dominated
THEMIS REGIO
Corona Dominated
E. EISTLA REGIO
Corona Dominated
300.0
250.0
200.0
150.0
100.0
50.0
0.0
ADC (km)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
SWELL HEIGHT (km

Fig 5

Fig 6



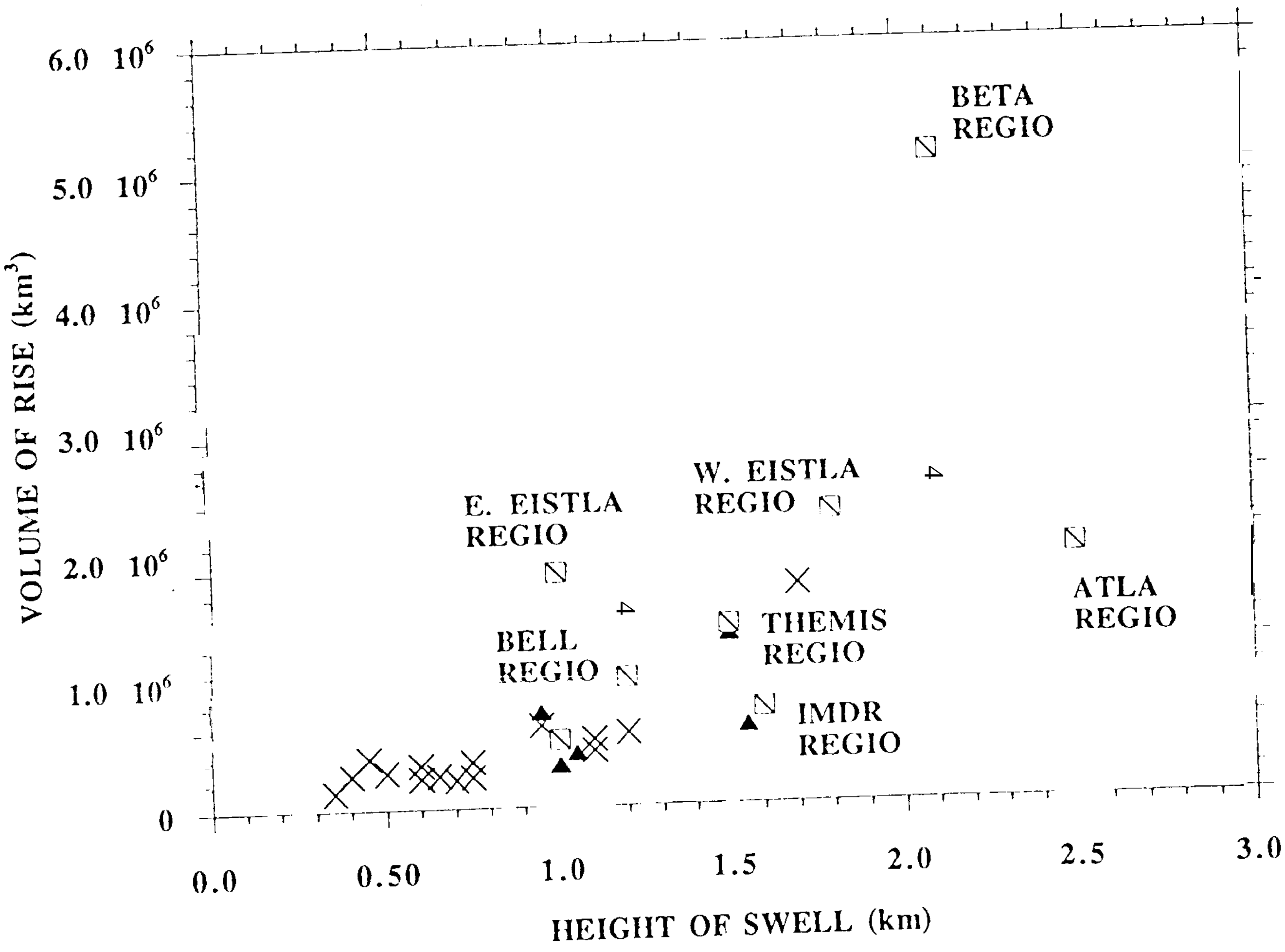

BETA REGIO
W. EISTLA REGIO
E. EISTLA REGIO
BELL REGIO
THEMIS REGIO
IMDR REGIO
ATLA REGIO
4
4
VOLUME OF RISE (km³)
6.0 10⁶
5.0 10⁶
4.0 10⁶
3.0 10⁶
2.0 10⁶
1.0 10⁶
0
0.0
0.50
1.0
1.5
2.0
2.5
3.0
HEIGHT OF SWELL (km)

Fig 8